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INVESTIGATION, ANALYSIS AND MANAGEMENT OF TUNNEL INFRASTRUCTURE SYSTEMS IN GEO-TECHNIQUE

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ABSTRACT
In this paper, a methodology for innovative developments in tunnel infrastructures using geotechnical systems and a combination of probabilistic analysis for rock-mass grading is presented. Exploratory tunnels are commonly used for examining the geotechnical and structural aspects of proposed tunnel alignments. The data was collected from research of an exploratory tunnel, at the Technical University of Vienna, Austria. The knowledge and experience of the New Austrian Tunneling Method (NATM), was used to evaluate the risks associated with design details for the final tunnel extension. The author has developed a deterministic model based on Monte Carlo simulation, which is capable of predicting outcomes in total project considering terms of cost, duration and potential probabilities related to various rock mass behaviours for optimizing excavation methods, alignment, grade and support measures as well as the final lining.
Keywords: Probabilistic Analysis, tunnelling infrastructures, NATM, evaluation of risks, rock mass grade, duration of project management, project planning and Ground investigation.

1. INTRODUCTION

Modern tunnelling offers a wide range of highly developed construction methods for underground excavation and final lining. Overall, we must accept that an ideal method for every tunnel building and every ground condition does not exist.
In Austria, the famous New Austrian tunnelling Method (NATM) is almost entirely applied in traffic tunnel constructions. This method driven by underground means with machinery support allows the production of nearly any tunnel with more or less any cross section depending on the existing bearing capacity of rock. Compared with other construction methods the advantage of NATM is the flexibility. Changes of cross sections and intersections with other tunnel profiles can be performed with less obstruction of the heading cycle. This flexibility comes from the way of using different rock support measures, which additionally mobilise the self-bearing capability of rock and allow a systematic adjustment. The geometry of the cross section can be enlarged or reduced by excavation and simultaneous support in the necessary scale without reducing the bearing capacity. This method is ideal for tunnels with changing cross sections, enlargements, station and similar buildings. In urban loose ground conditions, it is often necessary to strengthen the ground with supporting measures. The construction methods of foundation engineering give the opportunity to improve loose ground with compaction, injection and ground water lowering. Fully mechanized shield machines come to an economic interest when the contract sections are long enough. Besides safe

work conditions for miners the tunnel gets its fully bearing final segmental lining immediately after excavation. A great disadvantage of shield machines is their specialized construction for narrow hydro-geological soil conditions. When ground quality changes often and for a longer period or large rocky obstacles come into the bore head the performance goes down immediately and in worse cases it may come to a standstill. Opposite to soft ground tunnelling is the Tunnel Boring Machine (TBM) driving in hard rock mass with high overburden. Hard rock normally does not need much support. If necessary, modern tunnel boring machines allow support measures very close behind the bore head. The best TBM driving goes with continuous ground conditions since each boring machine is constructed to specific rock strength. Both TBM and shield require round cross section, which produces more excavation cubage.

As a rule, machine drivage is faster than drivage by underground means because of their continuity and performance. This disadvantage may be compensated by NATM drivage because of the opportunity to conquer a tunnel simultaneously from different headings. Modern tunnelling often requires a combination of both possibilities to come to an optimization of costs and technique. TBM drivage brings its advantages best with unsupported tunnel ground while NATM drivage works quite well under bad ground conditions. For this research, a trial tunnel was mined as part of the geotechnical investigations for the Kaponig Tunnel extension which is part of the double-track high-speed rail development. The New Austrian Tunneling Method (NATM) was used to mine an uphill section heading towards the mountainside tunnel portals.

2. GENERAL TUNNELLING CONSTRUCTION

Innovative techniques in tunnelling make high and various demands on construction. A tunnel as a building meets a certain function. Generally, all underground structures are used to be condensed in the common word tunnel. Technicians make a distinction between the kind of structure, the method of production and the size. They usually distinguish between galleries, tunnels, caverns and shafts. For example in mining, tunnels or galleries are simply a means to an end, so they are built to get to the face as easily as possible to bring the underground getting quickly back to the shaft. For traffic routes, the tunnel becomes the real traffic link. The tunnel itself becomes the main part of a certain road or railway. In previous times, tunnels were exclusively built to under-cross high mountain barriers. Today two other arguments are very often used for the decision to build a tunnel, lack of place and environmental aspects. The general tendency goes towards shifting traffic links into the ground to relieve civilization and environment. Rapidly growing urban areas and dwindling resources do not allow unlimited utilization of valuable ground especially in industrial nations.

3. EXPLORATORY TUNNELING

A) The knowledge of geotechnical conditions is the most important principle in the planning and execution of a tunneling project. The more comprehensively the preliminary investigations are carried out and the more valid they are, the better the basis for selecting the tunneling method.

B) From the cited geotechnical characteristic values and an overall appraisal of the geological and hydro-geological conditions of the subsoil, the following important technical data can be obtained, including:
– Stability of the face
– Nature and extent of the supporting measures
– Time lag between breaking-out and securing the open cavity
– Deformation behavior of the rock
– Influence of underground and/or groundwater

C) On the basis of the listed geotechnical characteristic values and construction data, including the relevant environmental factors, it is possible to select the construction method. It is also possible to divide the tunnel over its route into tunneling classes, which closely define the tunneling method, identify the performances to be applied per tunneling class and describe the degree of difficulty. Whereas the selection of the construction method is the prerequisite for allocation into tunneling classes (laid down by the client), the choice of the machine should be left as far as possible to the contractor in charge.

Exploratory tunnels are built so that engineers can use the Observational Method (OM), a tunneling management and design system that facilitates the use of modern measurement techniques. The OM's strength is its flexibility; design and management procedures that can be modified during the construction process itself. The proper use of exploratory tunnels can assist engineers and managers in a number of ways, Eisenstein.

Design Verification: designs can be checked and adjusted during excavation in order to ensure stability and cost issues;

Quality Control: engineers can determine if the tunnel is being constructed in accordance to the appropriate standards and stipulations;

Warning System: exploratory tunnels allow engineers the means to detect potential collapses, with the provision that the site is being continuously monitored. Exploratory tunneling, with the OM, allows engineers to take advantage of their own personal experience and gain first-hand information about a particular site. This knowledge, coupled with a proper understanding of standard tunneling procedures, can potentially reduce costs as well as provide an indication as to the safety of a particular site. Project managers using exploratory tunneling systems have the ability to alter the construction process in accordance to the specific features present at the site. This paper provides a brief description of the Kaponig tunnel, the drill and blast construction method as well as the Monte-Carlo simulation approach. Thereafter, analyses of productivity values observed during the tunnel construction are presented. The total time required to excavate the Kaponig tunnel was initially estimated to be 403.5 working days plus 28 working days allocated for unexpected ground infiltration water problem (≅14.40 months). *Figure 1* demonstrates the organizational chart for the tunneling crew.

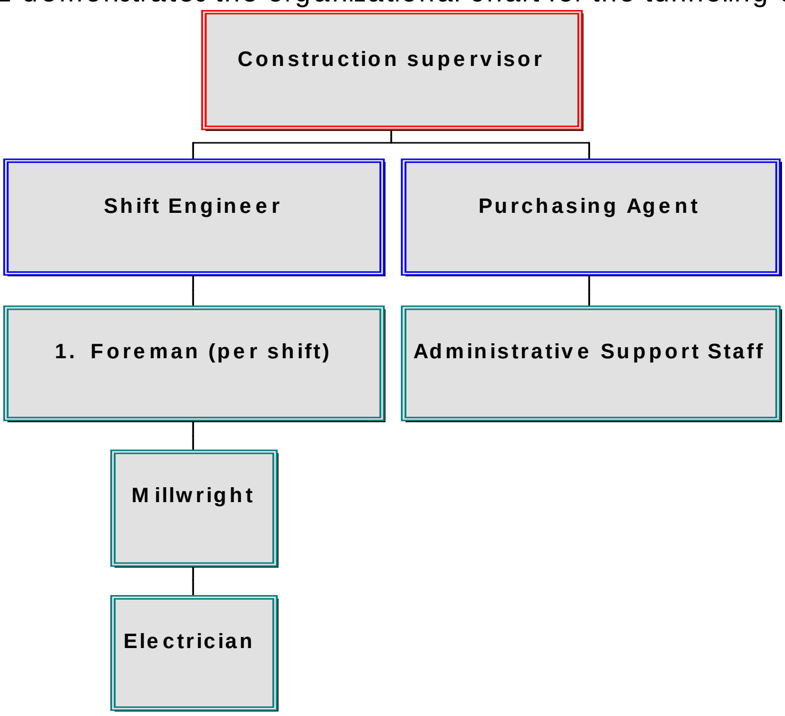

Figure: 1. Organizational chart for Construction Crew

The New Austrian Tunneling Method (NATM) is a flexible method, designed to take into account the variable conditions encountered at the tunneling face while mobilizing whatever intrinsic strength the rock possesses. This flexibility allows engineers to adapt and optimize their designs while the construction process is taking place. The basic methodology of NATM is simple: sprayed concrete is applied immediately to the tunnel wall as a temporary support during the tunneling process, and, if necessary, reinforced through the use of rock bolts, wire mesh and/or lattice girders. These components are employed so that as much elasticity as possible is retained in the initial support. This allows the stresses within the rock to relax and establish a revised equilibrium around the synthetic opening. Once this self-supporting equilibrium is re-established, the ground will sustain the opening and maintain its integrity with the minimum of extra support. The final liner is installed once the tunneling process has been completed.

The NATM is a classification scheme, a rock mass classification carried out after blasting. With respect to size-strength classifications, graphs are plotted according to point load strength versus block size. The International Society for Rock Mechanics (ISRM), classification includes the following parameters: discontinuity spacing, uniaxial compressive strength, and the angle of friction of fractures.

4. ANALYSIS OF TUNNELING CONDITIONS

Dates for each rock mass grade are due to the presence of extensive rock-mass grades 1 and 2 instead of the expected rock mass grades 3, 4, and 5 (based on geological and geotechnical investigations) and corresponding ground water inflow up to several hundreds of liters per second, the tunneling process needed to be interrupted frequently. Table 1 shows the estimated progress in terms of linear meters per day for each rock-mass grade and the corresponding efficiency adjustment factor for a given volume of water intake. Table 2 summarizes the actual length of rock-mass grade encountered during the excavation and its associated water intake level and productivity level (m/day).

The large water intake during the tunneling process required the enlargement of the sediment basin in order to handle the higher than expected sediment loading. Frequently, the locomotives derailed and dumped their load on the tracks making track repair work necessary. High track maintenance requirements delayed the excavation activities repeatedly. A tunnel of this size was expected to affect the groundwater conditions. For this reason, an extensive monitoring program was undertaken. During the construction of the pilot tunnel, a large amount of water inflow was encountered, and some of the springs in the surrounding area, experienced a decreasing discharge or were completely dried out. The decrease of discharge in some of these springs shows the influence of the tunnel construction on the hydro-geological conditions of mountain-groundwater body. Figure 2 summarizes the different components of the tunneling process and actual portions of the advancement work at the Tunnel.

Table: 1. Estimated Tunneling Progress for Each Rock-mass Grade

Rock-mass Grade		1	2	3	4	5	6	7	8	9
Estimated Production (see Table 2)	Original Estimate m/day	16.73	12.14	10.35	9.03	6.23	5.86	3.11	4.87	3.71
Water Intake: 0-5 l/s	Efficiency Factor	0.97	0.95	0.95	0.92	0.92	0.92	0.90	0.90	0.90
	Adjusted Estimate m/day	16.23	11.53	9.83	8.58	5.73	5.39	2.80	4.38	3.34
Water Intake: 5-50 l/s	Efficiency Factor	0.92	0.90	0.90	0.85	0.80	0.75	0.70	0.70	0.70
	Adjusted Estimate m/day	15.39	10.93	9.32	7.68	4.98	4.40	2.18	3.41	2.60

Note: to estimate the production in linear meters per day, multiply the estimated linear meters for the individual rock mass grade by the appropriate efficiency factor based on the expected water intake.

Table: 2. Construction period determination and necessary working days

Rock-mass Grade	l/s	linear meter	m/day	Working day	Probability of Rock-mass Grade	Probability of Water intake
1	0 - 5	61	16.23	3.76	0.0223	0.8841
	5 - 50	8	15.39	0.52	0.0029	0.1159
2	0 - 5	349	11.53	30.27	0.1276	0.9088
	5 - 50	35	10.93	3.2	0.0128	0.0911
3	0 - 5	553	9.83	56.26	0.2022	0.9171
	5 - 50	50	9.32	5.36	0.0183	0.0829
4	0 - 5	521	8.58	60.72	0.1905	0.9883
	5 - 50	38	7.68	4.95	0.0139	0.9916
5	0 - 5	531	5.73	92.67	0. 1941	0.9332
	5 - 50	38	4.98	7.63	0.0139	0.0668
6	0 - 5	317	5.39	58.81	0.1159	0.9242
	5 - 50	26	4.40	5.91	0.0095	0.0758
7	0 - 5	166	2.80	59.29	0.0607	0.9432
	5 - 50	10	2.18	4.59	0.0036	0.0568
8	0 - 5	6	4.38	1.37	0.0022	0.6666
	5 - 50	3	3.41	0.88	0.0011	0.3333
9	0 - 5	18	3.34	5.39	0.0066	0.7826
	5 - 50	5	2.60	1.92	0.0084	0.2174
Total		2735 m		403.5	0.0018	0.0252

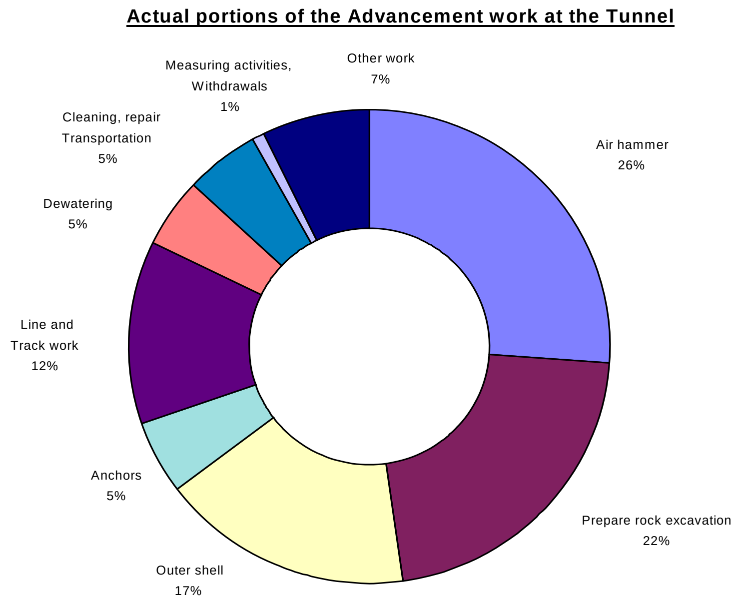

Figure: 2. Actual portions of the propulsion work at the Tunnel

4. THE DRILL AND BLAST TUNNELING PROCESS

The drill and blast technique is a very common tunnel excavation method. The heading sequence, length of advance and the required temporary ground support at face and heading govern the cycle time of the tunnel excavation. Temporary ground support measures have to be undertaken in accordance with the specific requirements to protect the works at the face and in the loading area in addition to stabilizing the tunnel section. Support is achieved by rock bolts and/or steel mesh, shot-Crete or in the case of extreme conditions, the installation of heavy steel ribs and nailing or bolting the face. The working stages, which govern the coordination of the excavation and ground support operations, need to be balanced with respect to both their efficiency and their economic viability. The drill and blast method employs a cyclic construction process with four key activity classes:

1. Drilling using a jumbo or otherwise

2. Loading/charging of explosives
3. Muck loading with tunnel excavators or side dumping loaders
4. Installation of temporary ground supports such as
• Rock bolting
• Erection of steel arch supports, and
• Shot-Crete.

Accurate drilling is required for tunnel section and optimal fragmentation of the rock. The drilling cycle includes the positioning of the jumbo, checking that the proper drilling pattern is employed to match the position along the tunnel length (station location), positioning the drilling arms (booms), and drilling the holes. Positioning of the drill jumbo is done with the laser. Computerized systems are commonly used to program the drilling booms to achieve a specific drill pattern (horizontal, angle, depth, spacing). Tunnel blasting technology consists of three components, namely:
1) Handling of explosives
2) Detonators
3) Loading and/or charging of the boreholes

There is a wide range of commercial explosives available for use in tunnel blasting; however, pump able site sensitized emulsion explosives are most commonly used in modern tunnels. The two emulsion components are pumped into the borehole and mixed by automatic means. The amount of explosive is volumetrically controlled based on the degree of fill necessary to achieve the desired fragmentation. Detonating systems used are either electric ignition or pyrotechnic tube ignition. Safety, simple installation, robustness, and accurate firing sequence of the individual holes are all highly desired attributes. Using proper detonators in the perimeter zone help to achieve a high cross-sectional accuracy and a clean break along the contour with low vibration and precise blasting. Mucking refers to the gathering together of material from where it has been deposited after the blast. The size of the individual rock fragments and the volume excavated per length of advance are essential criteria for selecting mucking equipment. Muck haulage can be undertaken via trains, belt conveyors, or dumpers. Commonly, a crusher is used at the transfer point for feeding the conveyor belt or the train.

5. MONTE CARLO SIMULATION

Statistical modeling, or Monte Carlo method, is commonly used to solve a wide range of multivariate problems in engineering and other sciences. Monte Carlo Simulation (MCS) is a versatile method of risk analysis that can be applied to diverse applications. For the construction industry, MCS can be applied to risk analysis of Construction Project Management (CPM) schedules and range estimating. MCS is a valuable tool if the activities are well defined and distributions can be readily developed. Monte Carlo Simulations can easily set up in a spreadsheet application such as Microsoft Excel. The basic steps involved in the process are outlined below. Each activity that has variable duration is described using a statistical distribution. This could be as simple as a uniform distribution between a minimum and maximum duration, a normal distribution described by a mean and standard deviation, or as complicated as a Beta or Exponential Distribution. The most common, and usually the easiest to generate, is a triangular distribution made up of the pessimistic, most likely and optimistic durations. A random number (step 1 below) is then mapped onto the distribution (step 2) to give the activity a possible duration for that run (step 3). After all the activities have been given a duration, the critical path is determined and a maximum duration of the project is calculated (step 4). This is repeated many times and the maximum duration is stored each time. This results in a distribution of the maximum duration of the project on which a risk analysis can be based. Depending on the distributions used for the activities, this distribution may or may not be normal, but; it is usually reasonable to assume normality. In terms of cost estimation the same process is used except that activity costs in an

estimate are described using the distributions and the total cost of the estimate is calculated on each run. The following algorithm can summarize Monte Carlo Simulation:
1. Generate a random number on the interval [0-1]
2. Transform the random number into an appropriate statistical distribution (e.g., normal, beta, uniform); the resulting number is referred to as a random variate.
3. Substitute the random variates into the appropriate variables in the model.
4. Calculate the desired output parameters within the model.
5. Store the resulting output for further statistical analysis.

Repeat steps 1-5 a number of times. Note: the generated uniform random numbers must be reiterated differently.

6. MONTE-CARLO SIMULATION OF EXCAVATION PROCESS

Evaluating the probability of different duration and cost scenarios is one of the principal reasons for using simulation to model construction processes. One of the primary objectives of using a simulation to model in construction processes is to evaluate and compare the performance of alternative approaches and fleet configurations. A common mode operation is to construct a simulation model for each approach, conduct a limited number of simulation experiments (runs), and then compare the competing alternatives based on the resulting average measure of their performance. The basic methodology described in the previous section was used to develop a simulation system for comparing the duration of a project (days) and actual completion times for each rock-mass grade of the total project using the NATM. Based on 500 cycles, probability values associated with different duration and cost estimates were established. Another application of simulation is for optimization of fleet configuration such as the number of muck cars or different mucking systems. In tunneling, most of the risk is due to geologic uncertainty, which is independent of the chosen construction method. Therefore, it is important that competing construction alternatives be compared under the same geologic conditions. Otherwise, the observed differences will be due to differences in the project geology rather than to the construction methods themselves. Conceptually, the solution to this problem is quite simple. The simulation runs for each alternative must be designed so that uncertainty influences each construction method in a similar manner. Since random numbers determines all uncertainty in a simulation model, the key is to ensure that the random numbers used for each method follow similar patterns. This approach, however, may introduce bias into the analysis.

The tunnel is assumed to serve as a connector for two commuter rail systems and thus requires no intermediate stations. All excavation must be performed underground with no intermediate shafts, starting at one of the existing stations. The current analysis assume the same excavation (drill & blast) and muck methods (train muck haulage) were used in all sections, but differ in the system used for initial tunnel support. The simulation created to model this tunneling process is described in the following: A Monte-Carlo simulation model was created in Microsoft Excel to generate the duration of tunneling projects as a function of rock mass grade. The model uses a series of random numbers to act as variables that occur during the tunneling process. The model first generates a random number to determine the rock mass grade that will be bored through. The rock mass grade is selected based on the percentages of rock hardness in the construction area as determined by the data collected from the pilot tunnel. From the knowledge of rock-mass grade, the length of time (referred to as base time) to complete the excavation of a segment 3m in length can be determined. The base time is then altered by ± 20% to account for the various processes that must take place depending on the rock-mass grade, which is present. Another random number is generated to obtain the water intake range. The random number determines the intake range (l/s) based on the percentage of linear meters (shown in Table 2). By comparing the rock-mass grade to the water intake, a predetermined efficiency factor, which accounts for minor delays that may occur during the tunneling process, is selected from *Table 2*. The model then divides the adjusted time by the efficiency factor to derive a final time required for the tunneling process, which is measured in time per 3 meters of progress. The model then calls a macro to this process a desired number of times to accommodate the length of the entire tunneling project being modeled. The result of this calculation yields the length of time required to complete any tunneling project as a number of days. This process is then, again, repeated 500 times to produce the probability distribution function (PDF) shown in *Figure 3* and cumulative distribution function (CDF) shown in *Figure 4.* The latter gives the probability of a tunneling project taking a given duration.

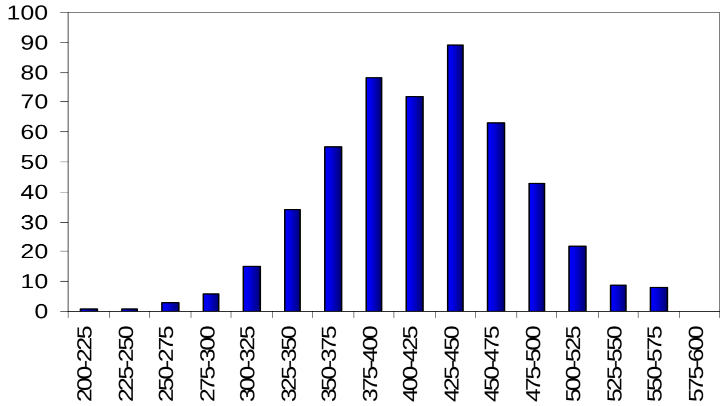

Figure: 3. The PDF based on the results from the simulation model

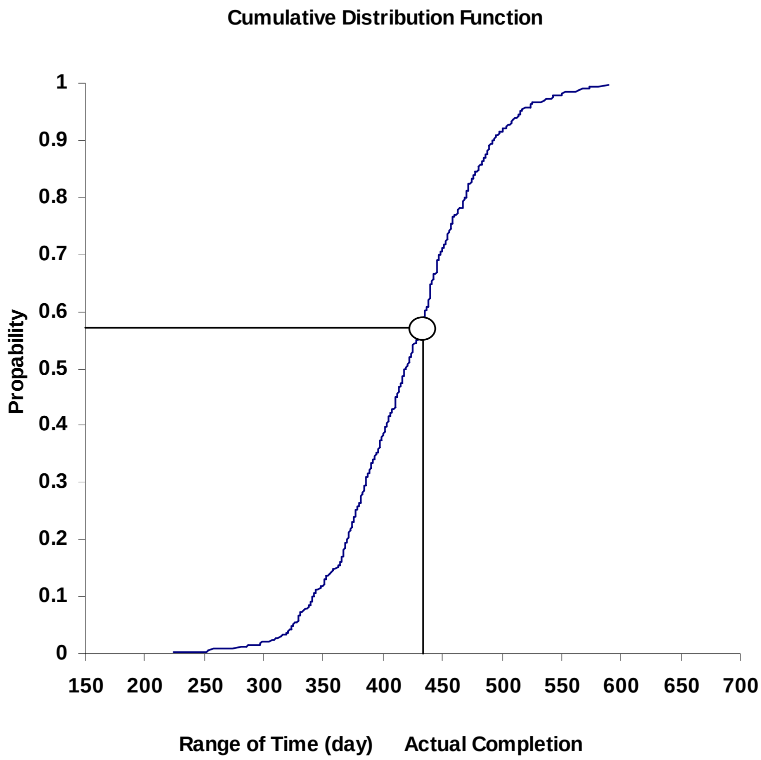

Figure: 4. The CDF based on the results from the simulation model

For construction, the excavation activity includes drilling holes into the tunnel face and loading them with explosives. This is followed by "shooting" the rock (retracting the jumbo, wiring the detonators, and detonating the explosives). For simplicity, these times have been made part of the duration of the "excavation" activity and thus firing is assumed to take zero time. Detonating is followed by the ventilation activity that to remove the smoke and toxic gases out of the tunnel. In order to bring back the jumbo and resume drilling again, all the debris resulting from the last shot must be removed. When mucking is done, excavation (i.e., drilling and loading) then the installation of the initial rock support can start. Consequently, excavation and support can occur at the same time. In order to detonate again, the excavation for the next round (drilling and loading of holes) must be complete, and sufficient initial support must have been placed so that, following the rock being blasted the length of unsupported tunnel is less than the maximum that is allowed for the current rock class. After the rock is blasted, the cycle will then be repeated. The excavation progress cycle (drilling, blasting and mucking) is called a 'round'. The tunnel geology is modeled as a discrete-state, discrete-space process. The first step starts out in rock-mass grade 1 and ends at rock-mass grade 9, as shown in Tables: 1 and 2. The rock-mass-grade transition probabilities from step to step. The excavation advance rates are expressed as linear meters per day.

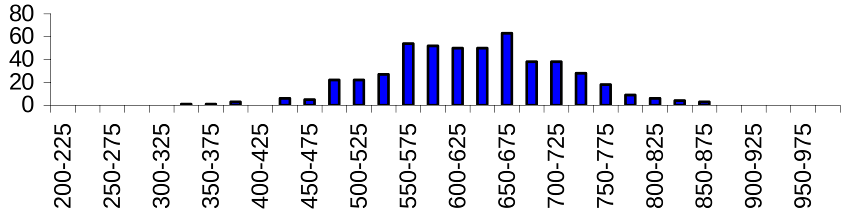

Figure: 5. The PDF based on the results from the simulation model for the second phase

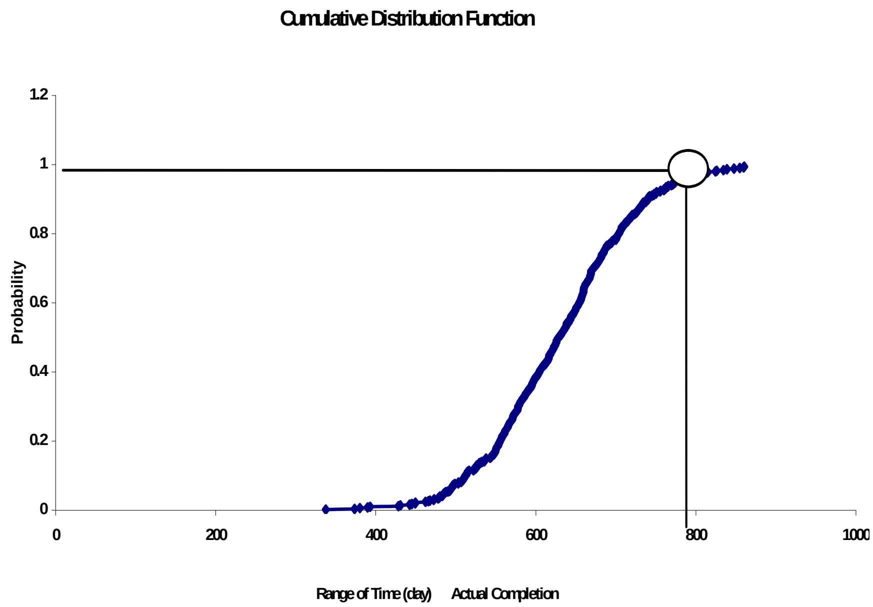

Figure: 6. The CDF based on the results from the simulation model for the second phase

7. COMPARISON OF ALTERNATIVE

Figures 3 and 4 show the results of the simulation. The probability function (PDF) indicates that the project could take as little as 225 days or as long as 550 days, with the most likely completion date of 425 days. The cumulative density function (Figure 4) reveals that the actual duration of the project 432 days corresponding to a probability value of 58%. Figures 5 and 6 demonstrate the results of the simulation for the second phase. The probability function (PDF) indicates that the project could take as little as 325 days or as long as 875 days, with the most likely completion date of 650 days. The cumulative density function *(Figure 6)* reveals that the actual duration of the project 790 days corresponds to a probability value of 94%.

By comparing both results, the model appears to give excellent results.

8. CONCLUSION

This paper discussed methodology for innovative developments in tunnel infrastructures using geotechnical systems. Exploratory tunnels indicate the appropriate construction method by providing information about geologic and hydro-geologic features and are essential monitoring tools for project managers. No matter what method is used, tunnelling will always contain some specific risks. To avoid unnecessary risks must be the major interest of any tunnelling professional. Most misfortunes happen due to carelessness, non-compliance with rules, negligence and underestimation of critical situations. In the case of this research, the exploratory tunneling work revealed that the initial estimates for ground water intake were misjudged; as a result, a larger sedimentation basin and construction equipment revisal and configuration would be required. The usefulness of exploratory tunnels could be further enhanced by combining productivity data, probability of encountering various geological and hydro-geological conditions and the Monte-Carlo simulation method to predict the probabilities associated with duration and cost. In view of the fact that static calculation is such a significant factor, the methods of calculation, for example the Monte Carlo Simulation, attempt to simulate different rock mass behaviours for grading, acting as an effective project management tool. However, with the permanent changing of ground formation, ingress of water along with various rock stabilities, even in the same heading and different fault formation do not allow committed rules and behaviour patterns. Ground behaviour can not be guaranteed, although by using the probabilistic analysis and investigations discussed in this paper, the possibility for optimization in future tunnel infrastructure systems may be achieved.

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